Binary Black Hole Mergers, Gravitational Waves & LISA

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ABSTRACT

The final merger of comparable mass binary black holes is expected to be the strongest source of gravitational waves for LISA. Since these mergers take place in regions of extreme gravity, we need to solve Einstein's equations of general relativity on a computer in order to calculate these waveforms. For more than 30 years, scientists have tried to compute black hole mergers using the methods of numerical relativity. The resulting computer codes have been plagued by instabilities, causing them to crash well before the black holes in the binary could complete even a single orbit. Within the past few years, however, this situation has changed dramatically, with a series of remarkable breakthroughs. We will present the results of new simulations of black hole mergers with unequal masses and spins, focusing on the gravitational waves emitted and the accompanying astrophysical “kicks.” The magnitude of these kicks has bearing on the production and growth of supermassive black holes during the epoch of structure formation, and on the retention of black holes in stellar clusters.

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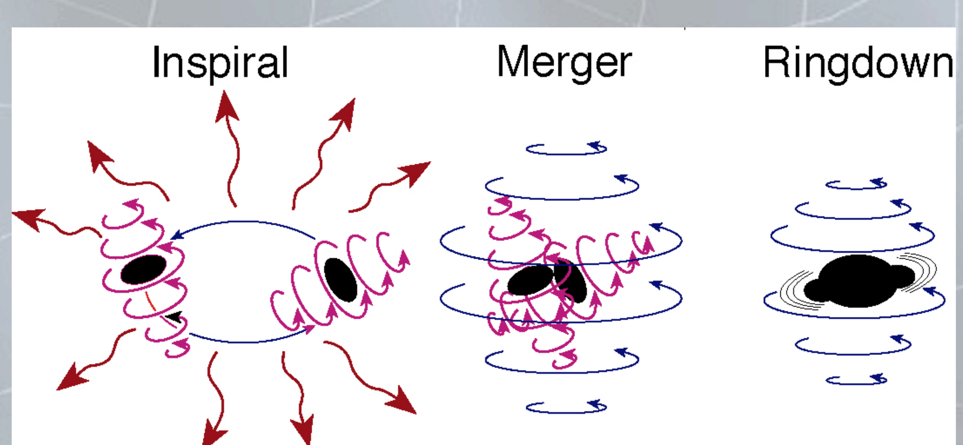
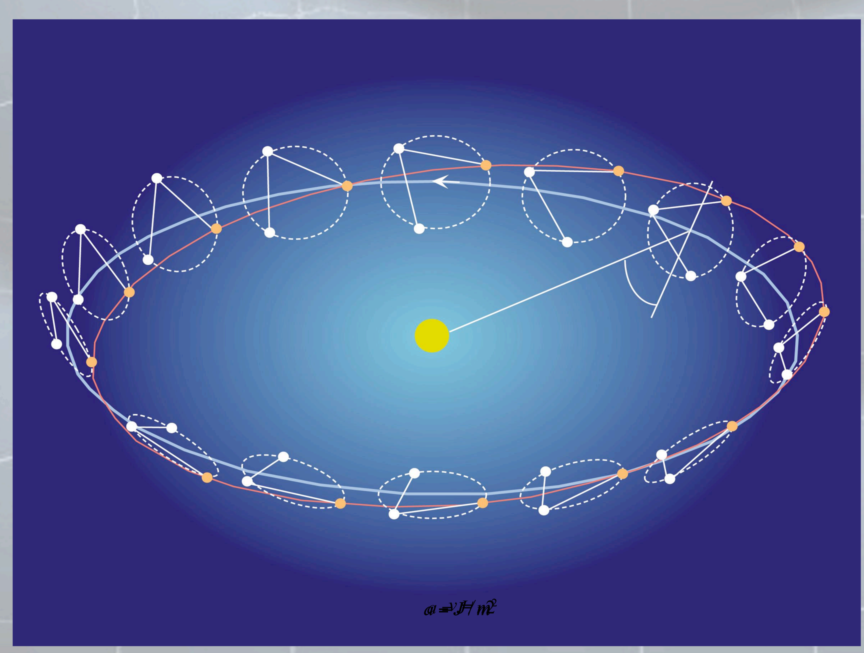
Binary Black Hole Mergers

A binary system of two close black holes will generate gravitational radiation, losing energy and angular momentum until the black holes merge to form a single remnant black hole. These systems are predicted to be the among strongest sources of observable gravitational radiation for both ground-based gravitational wave instruments and the Laser Interferometer Space Antenna (LISA). Indeed, during the peak moments of radiation production, these mergers may be nature’s most energetic events since the big bang, producing energy at a rate of ~ 10^{23} L_{Sun}. Black hole mergers may occur for binaries over a broad range of mass-scales, from tens of solar masses to millions.



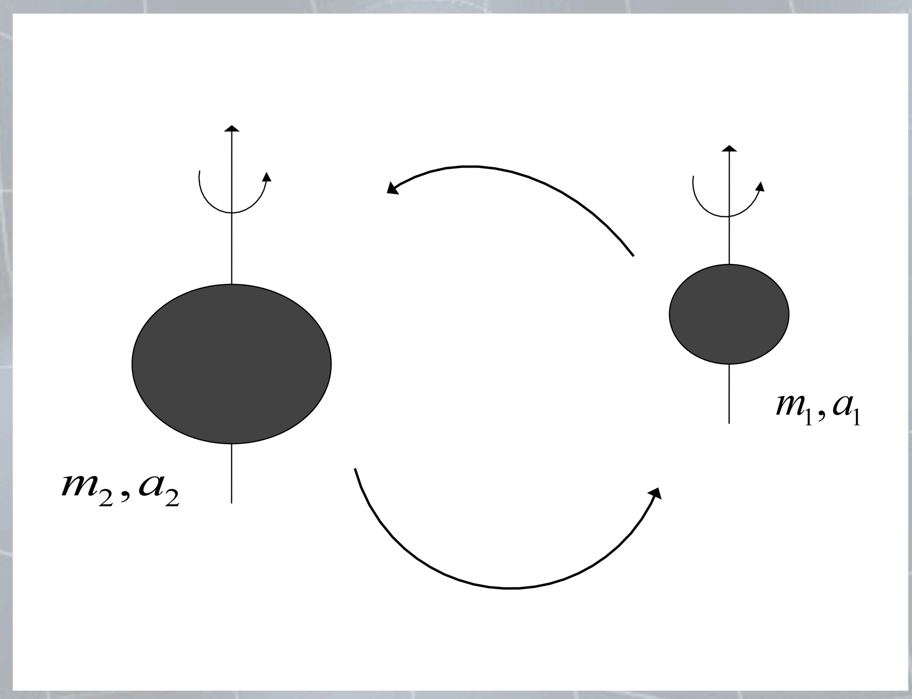
A Key LISA Source

LISA is expected to observe binary black hole systems with total masses in the range 10^4—10^7 M_{Sun}. These are expected to be the strongest LISA sources, producing signal-to-noise ratios into the thousands. Mergers of massive black holes at the centers of galaxies may trace galaxy formation *z* > 6. Because general relativity makes clean predictions for the waveforms from these mergers, these observations will provide fundamental test of gravitational theory for very strong gravitational fields. Black hole mergers can also serve as standard candles, providing absolute distances for events which might be observed out to *z* > 10.



Astrophysical Black Hole Mergers

LISA will observe massive black hole mergers arising from mergers of galaxies containing central black holes. The black holes have masses m_1, m_2 and spin parameters a_1, a_2. For gas-rich (wet) galactic mergers, the black hole spins are expected to be aligned with the orbital angular momentum due to torques from the accretion disk (Bogdanovic, Reynolds, & Miller 2007).



Gravitational Recoil

The gravitational radiation emitted by the merger carries linear momentum. When the black holes have unequal masses or spins, this radiation is “beamed,” with more radiation coming out in one direction. Since momentum is conserved, the merged remnant black hole receives a “kick” in the opposite direction.

Since the largest part of the kick is produced during the strong-field merger, fully general relativistic simulations of black hole mergers are needed to provide accurate values for the kick velocity.

TABLE 1

INITIAL DATA PARAMETERS. RUNS ARE LABELED “EQ” FOR EQUAL MASS AND “NE” FOR UNEQUAL MASS. J_1 AND J_2 ARE THE SPIN ANGULAR MOMENTA OF THE TWO HOLES, EITHER ALIGNED (POSITIVE) OR ANTI-ALIGNED (NEGATIVE) WITH THE ORBITAL ANGULAR MOMENTUM. m_{p1} AND m_{p2} ARE THE DIRECTLY SPECIFIED PUNCTURE MASSES OF THE HOLES. P IS THE INITIAL TRANSVERSE MOMENTUM ON EACH HOLE, WHILE L IS THE INITIAL COORDINATE SEPARATION OF THE PUNCTURES.

Run	$J_1(M^2)$	$J_2(M^2)$	$m_{p1}(M)$	$m_{p2}(M)$	P (M)	L (M)
NE_{--}	-0.032	-0.072	0.374	0.586	0.119	7.05
NE_{-+}	-0.032	0.072	0.374	0.586	0.119	7.05
NE_{0-}	0.000	-0.072	0.374	0.586	0.119	7.05
NE_{00}	0.000	0.000	0.382	0.584	0.119	7.05
NE_{0+}	0.000	0.072	0.374	0.586	0.119	7.05
NE_{+-}	0.032	-0.072	0.374	0.586	0.119	7.05
NE_{++}	0.032	0.072	0.374	0.586	0.119	7.05
EQ_{+-}	0.050	-0.050	0.480	0.480	0.124	7.00

Calculating Kick Velocities

We have simulated black hole mergers with unequal masses and spins anti/aligned with the orbital angular momentum. The black holes have physical (horizon) masses m_1, m_2 and spin parameters a_1, a_2. The total mass is *M*. The magnitude of the spin angular momentum *J* is related to the spin parameter *a* according to $a = J/m^2$.

The table to the left gives the initial data parameters for our simulations. We set *G* = 1 and *c* = 1. We evolved these data sets with a numerical relativity code using adaptive mesh refinement to provide good resolution both in the dynamical regions near the black holes and in the outer regions where the gravitational waves are extracted.

The resulting recoil velocities for these runs are shown in the figure below.

(Baker, et. al., ApJ 668, 1140 (2007))

TABLE 2

PREDICTED VERSUS COMPUTED KICK SPEED. RUNS LABELED “S0.##” ARE TAKEN FROM HERRMANN ET AL. (2007A), WHILE RUNS LABELED “R#” ARE TAKEN FROM KOPPITZ ET AL. (2007).

Run	q	$\hat{a}_1$	$\hat{a}_2$	v_{num}	v_{pred}	$\frac{\lvert\Delta v\rvert}{v_{num}}$(%)
NE_{--}	0.654	-0.201	-0.194	116.3	119.5	2.7
NE_{-+}	0.653	-0.201	0.193	58.5	58.2	0.5
NE_{0-}	0.645	0.000	-0.195	167.7	153.1	8.7
NE_{00}	0.677	0.000	0.000	95.8	98.6	2.9
NE_{0+}	0.645	0.000	0.194	76.9	71.7	6.8
NE_{+-}	0.655	0.201	-0.194	188.6	181.9	3.6
NE_{++}	0.654	0.201	0.194	83.4	92.4	10.8
EQ_{+-}	1.001	0.198	-0.198	89.8	92.6	3.2
S0.05	1.000	0.200	-0.200	96.0	93.8	2.3
S0.10	1.000	0.400	-0.400	190.0	187.6	1.2
S0.15	1.000	0.600	-0.600	285.0	281.5	1.2
S0.20	1.000	0.800	-0.800	392.0	375.3	4.3
r0	1.000	-0.584	0.584	260.0	274.0	5.4
r1	0.917	-0.438	0.584	220.0	220.8	0.3
r2	0.872	-0.292	0.584	190.0	178.1	6.3
r3	0.848	-0.146	0.584	140.0	141.9	1.4
r4	0.841	0.000	0.584	105.0	110.4	5.1

Modeling Kick Velocities

We have modeled our results based on scalings for the effects of mass- and spin-asymmetry in the post-Newtonian (PN) approximation. We assume that the magnitudes of the kicks induced by mass- and spin-asymmetries each scale independently with the PN-predicted scaling, but that the directional alignment of these two contributions to the kick may differ by some angle. The total kick would then take the form:

$$v = V_0\left[32q^2/(1+q)^5\right]\left((1-q)^2 + 2(1-q)K\cos\theta + K^2\right)^{1/2}$$

where

$$K = k(q\hat{a}_1 - \hat{a}_2)$$

k = relative scaling of spin and q - induced contributions

θ = angle between directions of spin and q - induced kicks

We have tested our formula using data from our simulations, as well as from published results from Koppitz et al. (2007) and Herrmann et al. (2007). Our best fit to all simulation data give the following values for the parameters: V_0 = 276 km/s, θ= 0.58 rad, *k* = 0.85.

The table at left compares our predictions with the kick velocities obtained by numerical simulations.

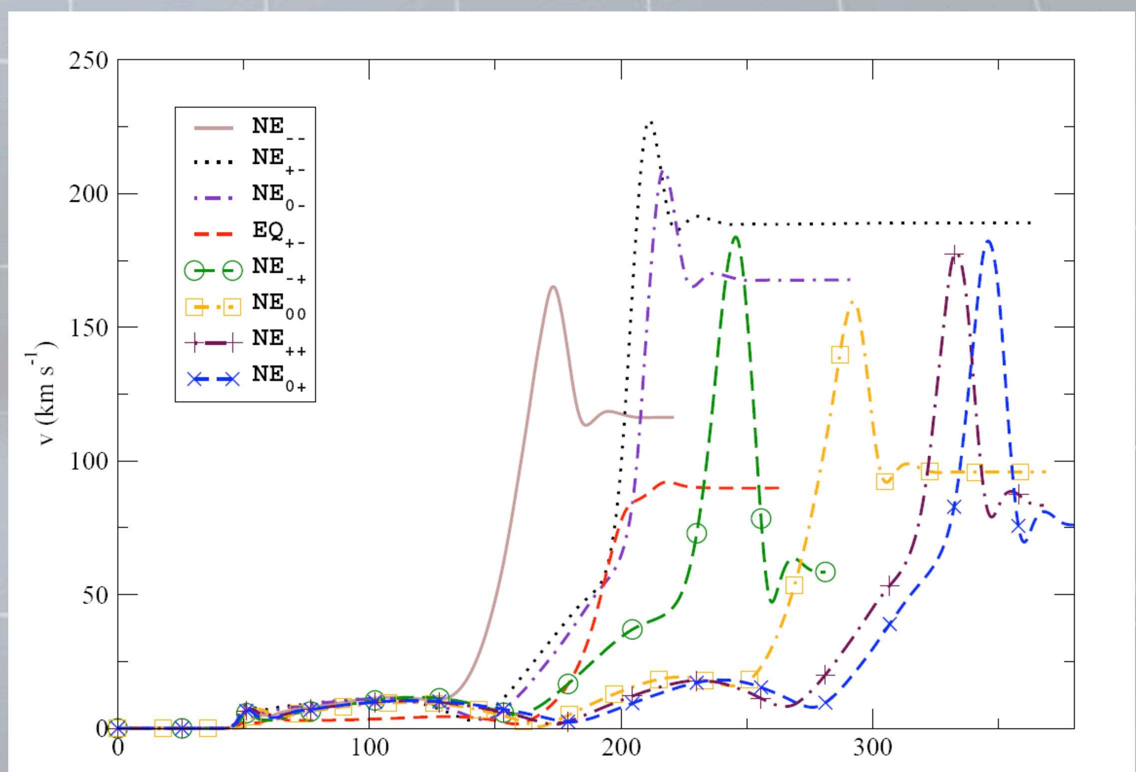


FIG. 3.— Aggregated recoil kicks from all runs listed in Table 1. The merger time for each binary matches the peak in its kick profile; the relative delay in merger times between data sets differing in initial spins is consistent with the results of Campanelli et al. (2006c). All configurations show a marked "un-kick" after the peak, with the exception of the equal-mass case, EQ_{+-}.